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Pressurization and Expulsion of Cryogenic Liquids: Generic Requirements for a Low-Gravity Experiment

Neil T. Van Dresar and Robert J. Stochl
Lewis Research Center
Cleveland, Ohio

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PRESSURIZATION AND EXPULSION OF CRYOGENIC LIQUIDS: GENERIC REQUIREMENTS FOR A LOW-GRAVITY EXPERIMENT

Neil T. Van Dresar and Robert J. Stochl
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Summary

Requirements are presented for an experiment designed to obtain data for the pressurization and expulsion of a cryogenic supply tank in a low-gravity environment. These requirements are of a generic nature and applicable to any cryogenic fluid of interest, condensible or noncondensable pressurants, and various low-gravity test platforms such as the Space Shuttle or a free-flyer. The paper provides discussion of background information, the thermophysical process, preliminary analytical modeling, and experimental requirements. Key parameters, measurements, hardware requirements, procedures, a test matrix, and data analysis are outlined.

Introduction

Current interest in pressurized transfer of cryogenic fluids stems in part from NASA's plans for an ambitious Space Exploration Initiative including manned voyages to the Moon and Mars. These activities will require large amounts of cryogenic fluids and the ability to efficiently transfer these fluids from one location to another. Low-gravity (low-g; acceleration level of 10^{-3} g or less) transfer will be a vital technology for successful operation of Earth-to-orbit tanker vehicles, orbiting depots, space transportation vehicles, and other spacecraft of the future.

Supply tank pressurization and expulsion is the initial step of a complete fluid transfer process that is expected to include transfer line and receiver tank chill down and unvented or vented fill of the receiver tank. Tank pressurization, using either inert or autogenous gases, is a relatively straightforward and reliable procedure that NASA has employed to expel cryogenic propellants from launch vehicle tankage.

(Strictly speaking, autogenous pressurant gas is generated by vaporizing liquid that is withdrawn from the propellant tank. Herein, autogenous pressurization refers to the use of the gaseous phase of the cryogen, regardless of its source.) Pressurized expulsion of cryogens from space-based storage tanks is considered a viable component of cryogenic fluid management for space applications. The technique involves the injection of a gaseous pressurant into the ullage space of a cryogenic supply tank thereby raising its pressure from some base level to the desired transfer level (ramp process). Once the desired transfer pressure is obtained, liquid cryogen is discharged from the tank via a connecting line to a receiver tank (expulsion process). A brief hold period between the ramp and expulsion periods is often utilized to allow stabilization of tank pressure and temperatures before expulsion is initiated. Use of condensible and non-condensable pressurant gases are both of interest.

The need for accurate predictions of pressurant requirements becomes apparent when one considers that an insufficient amount of pressurant could ultimately lead to mission failure (due to an incomplete transfer process) while an excess could result in considerable weight and cost penalties. Pressurant can either be stored as a gas in high pressure bottles and/or generated as required from the liquid cryogen with a vaporizer. It becomes important, therefore, to accurately predict the amount of pressurant needed for various transfer operations in order to correctly size either the storage bottles and/or vaporizer subsystem.

Numerous experimental studies conducted by NASA (refs. 1 to 7) in the 1960's and 70's investigated the pressurized discharge of a cryogenic fluid from supply tanks in a 1-g environment. The majority of these tests were performed in large-scale propellant tanks using rapid expulsion times on the order of 1 to 10 min to simulate propellant tank expulsion during an Earth-to-orbit ascent. In contrast, the planned fuel

transfer operations in space (tanker-to-depot or depot-to-space transfer vehicles) are expected to have transfer times on the order of hours. Any pressurized expulsion that uses relatively warm gas introduces a number of complex energy transfer processes within the tank. For a rapid discharge operation, these thermal effects can be simplified; as the transfer time increases (lower discharge rates), it becomes necessary to include these thermal effects in a more detailed analysis. Data over the appropriate range of anticipated expulsion times will aid the development of improved analytical models.

Preliminary analysis has shown considerable uncertainty in estimating pressurant requirements, depending upon the magnitude of the thermal energy transfer occurring between the pressurant and the initial fluid contents of the tank. The magnitude of this thermal energy transfer is in turn dependent upon the acceleration level, tank geometry, characteristics of the liquid-vapor interface, and thermal and mass transport processes within the tank. Because the system response is gravity dependant, it cannot be completely simulated with ground-based tests. In addition, low-g analysis will be considerably more difficult to perform than that for normal-g.

Accurate predictions require an improved understanding of complex low-gravity fluid dynamics and interfacial heat and mass transport phenomena in two-phase cryogenic systems. Experimental data obtained from an on-orbit pressurization and expulsion experiment would allow the development (and subsequent validation) of analytical models over the appropriate range of expected operating parameters such as flow rate, pressure, and inlet temperature. These models are needed to predict pressurant requirements for space missions and to optimize the operating parameters of the transfer system.

This document describes the requirements for low-g pressurization and expulsion experiments, which could be performed either on the Space Shuttle or a free-flying test platform. The purpose of the experiments is to investigate the pressurization and expulsion process in a low-g environment. The objectives of the pressurization and expulsion experiments are as follows:

- (1) Demonstrate the feasibility of pressurized transfer technology in a low-g environment.
- (2) Collect data to be used to develop an analytical model.
- (3) Observe unexpected low-g phenomena if any.
- (4) Validate an analytical model after its development.

Nomenclature

F	fill level (liquid volume/tank volume)
h	enthalpy
m	mass
Q	energy input from environment
U	system energy
u	specific internal energy
V	volume

Greek

ρ density

Subscripts

a	initial ullage component
b	added ullage component (pressurant)
f	saturated liquid
g	saturated vapor
i	inflow
l	liquid
o	outflow
p	pressurant
t	tank
u	ullage (portion of tank occupied by vapor/gas)
x	transferred at liquid-vapor interface
1	initial condition
2	final condition

Pressurization and Expulsion—The Thermophysical Process

As a cryogen is pressurized, warm gaseous pressurant transfers heat to the cryogen, tank wall, and internal hardware. If the pressurant is condensible, additional heat transfer occurs when the pressurant condenses due to the release of its heat of vaporization. The combined heat and mass transfer processes greatly influence the tank pressure, and thus, the amount of pressurant required for a transfer operation. In addition, heat transfer to the liquid increases its temperature; potentially this could lead to increased complications during the transfer process and a less desirable thermodynamic state of the transferred cryogen. The pressurant injection temperature and diffuser design/location are some of the parameters influencing the thermodynamic state of the cryogen during expulsion.

Common practice is to introduce the pressurant gas into the ullage through a diffuser so that high velocity impingement on the liquid, wall, and internal hardware is minimized. Diffuser design is not an exact science and many types have been used. Normal-g tests at NASA using ambient temperature pressurant (ref. 8) have shown that situations exist where direct impingement of the pressurant on the liquid-vapor interface reduces pressurant requirements by inducing liquid evaporation.

In normal-g, heat transfer occurs between the tank wall and the pressurant; while in true zero-g, the wall may be completely wetted and heat transfer could occur only between the cryogen and the pressurant gas. For low-g, the interaction of the pressurant and the wall will be significantly less than for 1-g, but not necessarily negligible. The primary process of interest, therefore, is the heat and mass transferred at

the liquid-vapor interface between the pressurant and the cold cryogen. Also of interest are the degree of temperature stratification in the tank and the amount of heat transfer to the wall and internal hardware. The quantity of pressurant required is an indirect measurement of the amount of heat transferred from the pressurant.

In a low-g environment, the location of the liquid contents of a tank may not be well defined. Intense pressurant-liquid interaction might be unavoidable under conditions such as when the tank has a high fill level or during liquid sloshing (ref. 1). In addition, experiments (ref. 9) performed by the authors with liquid hydrogen show that extreme pressurant collapse and liquid heating occur when autogenous pressurant gas is directly injected into the liquid. Developers of low-g pressurization and expulsion technology should attempt to minimize pressurant-liquid interaction as much as possible.

Preliminary Analytical Modeling

Two simplified models have been developed to provide approximate lower and upper bounds on the pressurant requirement for a pressurization and expulsion process with given initial tank conditions and known pressurant inlet conditions. The first is an isentropic pressurization and expulsion process, which leads to relatively low pressurant requirements. The second assumes thermal equilibrium is attained in the pressurization and expulsion process, which leads to considerably higher pressurant requirements. These processes may not establish absolute minimum and maximum pressurant needs, but they are expected to be sufficient for bounding actual requirements. The models are valid in any gravitational environment. The isentropic process is an idealized situation characterized by the use of a well-designed pressurant diffuser under quiescent conditions without energy transfer. The equilibrium model is considered as an extreme case representative of well-mixed conditions due to vigorous sloshing or intense pressurant-liquid interaction. Equations for the models are provided below:

Isentropic Model

$$m_p = \rho_{b2} V_t \left[1 - F_2 - (1 - F_1) \frac{\rho_{a1}}{\rho_{a2}} \right] \quad (1)$$

Thermal Equilibrium Model

$$m_p = \frac{m_{f2} u_{f2} + m_{g2} u_{g2} - m_{f1} u_{f1} - m_{g1} u_{g1}}{h_i - h_0} + \frac{(m_{f1} + m_{g1} - m_{f2} - m_{g2}) h_0}{h_i - h_0} \quad (2)$$

where

$$m_{f_{1,2}} = F_{1,2} V_t \rho_{f_{1,2}} \quad (3)$$

and

$$m_{g_{1,2}} = (1 - F_{1,2}) V_t \rho_{g_{1,2}} \quad (4)$$

The need to develop an improved analytical model which predicts actual pressurant requirements is apparent from the example shown in figure 1 for expulsion of liquid hydrogen using para-hydrogen as the pressurant. (When using gaseous hydrogen as the pressurant, the composition should be considered, due to the heat of conversion from ortho- to para-hydrogen.) This figure compares the predictions of the isentropic and equilibrium models for pressurization and expulsion to the 5 percent fill level (by volume). Initial fill level is plotted on the abscissa and spans a range of 5 to 95 percent. The difference between the models can be as much as a factor of 3.5 when transferring 90 percent of the tank volume.

Experimental Requirements

Pressurization and expulsion tests may be performed either as the principal experiment set or in conjunction with other transfer experiments. The following requirements are specified as an outline for low-g pressurization and expulsion tests:

General Requirements

Working Fluid.—Commonly used liquid propellants (e.g., fuels and oxidants such as hydrogen and oxygen) are most favored. Nitrogen, used in life support systems, is also of interest. Due to safety considerations, hydrogen or oxygen testing will require a free-flying platform such as COLD-SAT (ref. 10), while nitrogen can be tested on the Space Shuttle, as in the proposed CONE (ref. 11) program.

Presently, there is much to be learned with regard to low-g fluid dynamics, as well as heat and mass transport phenomena in cryogenic fluids (at all acceleration levels). Some valuable precursory information on the low-g fluid dynamics of the pressurization and expulsion process could be obtained from simpler experiments using simulant fluids with appropriate scaling (i.e., similar Bond, Weber, and Reynolds numbers). However, use of a cryogenic fluid will be necessary to obtain correct scaling of interfacial transport phenomena (i.e., Jakob number and similar vapor-to-liquid property ratios such as density and specific heat).

Pressurant Gas.—Both autogenous and noncondensable pressurants are of interest. Autogenous systems avoid the problem of cryogen contamination by the pressurant and will be preferred for vessels which are refilled in space, such as an on-orbit depot. Noncondensables may be viable for nonrefillable tankage or ground-based spacecraft such as an Earth-to-orbit tanker. Noncondensables may also be used in refillable tankage that is completely emptied and vented to

space vacuum prior to refill. A single noncondensable pressurant system can pressurize the fuel, oxidizer, and life support supply tankage.

Acceleration Level.—Data is desired in an acceleration range spanning micro- to normal-g. Future spacecraft will operate in low-g conditions where the liquids may be either settled or unsettled; pressurized expulsion systems could be optimized for each situation if sufficient data is available. For an on-orbit pressurization and expulsion experiment, it is desirable to test with both settled and unsettled tank conditions. The settled environment will be similar to that at 1-g except that the liquid-vapor interface may be curvilinear. Data taken at a settled condition will be compared to 1-g data to determine the necessary modifications of high Bond number analytical models. The unsettled experimental condition will provide insight to the low Bond number behavior of pressurization and expulsion that will guide future analytical modeling for low-g fields.

Tank Geometry.—For experimental investigation, simple tank shapes are desired to reduce the complexity of experimental analysis and to maximize the conformity of the experiments with analytical modeling capabilities. An oblong tank with a length-to-diameter ratio greater than unity will allow testing under both fully- and partially-wetted wall conditions by varying the initial fill level. The geometry should also be representative of future spacecraft tankage.

Tank Wall/Internal Hardware.—Since full-scale spacecraft tanks have a small tank mass-to-volume ratio, it is important to simulate this condition by using thin-wall tanks in the experiment. The total heat absorbed by the tank wall and internal hardware should be small compared to the energy added by the pressurant and energy absorbed by the ullage and liquid.

Wall Heat Flux.—Total external heat leak into the tank must be small compared to the energy transfer due to pressurant inflow and liquid outflow. The tank thermal control system, as needed to maintain the appropriate on-orbit thermal state of the working fluid, will be adequate for pressurization and expulsion experiments.

Diffuser.—At least one tank should be equipped with a pressurant diffuser designed to minimize vapor mixing and impingement of pressurant gas on the liquid. This diffuser should be located at the end of the tank opposite the settled liquid location. An additional diffuser which promotes liquid impingement also is of interest. Various diffusers could be installed in a single supply tank or, if available, in multiple tanks.

Pressurant Source.—Sources of gaseous condensable and/or noncondensable pressurant with sufficient storage capacity to meet the pressurant demands of the test matrix are required. The supply must be capable of maintaining tank pressure during expulsions at the specified outflow rates. A device that allows replenishment of the pressurant supply from the liquid propellant, as the need arises, may be considered as a means of reducing the test package weight. The

pressurant must be supplied at controlled temperatures as much as possible.

Working Fluid Re-use Capability.—To perform a meaningful number of expulsion experiments, it is necessary to refill the supply tank. Otherwise, tests will be limited to a sequence of partial expulsions where the expelled liquid is not recycled. A receiver tank and the capability to refill and recondition the supply tank will greatly expand the test matrix. The receiver tank and transfer line should be constructed to minimize heating of the fluid.

Key Parameters

Key parameters for the pressurization and expulsion experiment are identified in Table I. Also indicated in the table is whether the parameter is parametrically varied, maintained constant, or measured but not controlled. Parenthetical quantities are measurements from which the parameter can be quantified.

TABLE I.—KEY PARAMETERS

Specific enthalpy (temperature) of incoming pressurant	Parametric variation
Mass flowrate or expulsion rate of expelled liquid	Parametric variation
Acceleration level (Bond Number)	Parametric variation
Design and location of the diffuser	Parametric variation
Initial and final tank fill levels	Parametric variation
Tank pressure	Parametric variation
Condensible/noncondensable pressurant	Parametric variation
Ramp rate	Maintain constant
Hold time	Maintain constant
Mass flowrate of incoming pressurant	Measured
Specific enthalpy (temperature) of expelled liquid	Measured
Initial and final temperature profiles (liquid or vapor) in tank	Measured
Thermal energy (temperature) change of the tank wall	Measured

Measurements

Measurement requirements for the pressurization and expulsion experiment include:

- (1) An adequate number of temperature measurements located inside the tank(s) to characterize the mass and energy of the fluid (liquid and vapor) prior to, during, and after the pressurization and expulsion process.
- (2) An adequate number of temperature measurements on the tank walls to characterize any change in wall thermal energy.
- (3) Temperature and pressure of the pressurant gas as it enters the tank and the temperature of the liquid outflow.
- (4) Pressure in the tank(s).

- (5) Flowrate and total mass of both pressurant gas into and liquid out of the tank.
- (6) A sufficient number of liquid-vapor sensors to determine phase locations in the tank.
- (7) Acceleration measurements over entire duration of pressurization and expulsion test.

All flow measurements (flowrate, temperature and pressure) should be made at a rate sufficient to adequately characterize (by integration) the mass inflow and outflow. Internal tank temperatures and pressure will, as a minimum, be recorded prior to the ramp, at the end of the ramp, at the end of the hold, and at the end of transfer. The measurements and instrumentation locations are summarized in Table II. Range of the measurements depend upon the cryogenic fluid selected for experimentation. Fluid temperatures, for example, will range from below saturation to ambient (for the spacecraft). Temperatures must be measured to within 1 °R or better. Accuracy for other measurements (except acceleration) should be on the order of ± 1 to 2 percent of full scale.

Table II.—MEASUREMENT REQUIREMENTS

Physical property or state	Location
Liquid/vapor temperature	Inside supply tank
Liquid/vapor indication	Inside supply tank
Wall temperature	Tank wall
Outflow temperature	Tank outflow
Pressurant temperature	Pressurant inflow
Pressure	Supply tank
Pressure	Pressurant inflow
Mass flow	Pressurant inflow
Mass flow	Liquid outflow
Acceleration	Spacecraft

Hardware Requirements

Design requirements for much of the hardware are governed by the general requirements given above. Tank and diffuser construction should meet the above guidelines. The tank should be lightweight, but of sufficient strength to safely accommodate the pressure range of interest and the various loads encountered in spaceflight.

A liquid acquisition device (LAD) is required to ensure that liquid is available at the outflow port during low-g transfer. Liquid/vapor sensors should be installed near the entrance of the liquid discharge lines to indicate the presence of vapor during discharge.

A tank pressure control system is needed to maintain the desired tank pressure profiles during the ramp, hold, and transfer operations.

A liquid flow control system is required to maintain constant liquid flow rates during low-g vented fills or during vented operational transfers. An alternative to outflow control would be allowing the supply-receiver tank pressure differential to determine liquid flow rate.

The heat leak that comes into the test tank through necessary penetrations, supports, etc., must be at least an order of magnitude less than other sources of energy flow in or out of the tank.

Procedures

It is desired to collect as much tank pressurization and expulsion data as possible during all tests. This will require:

- (1) Repeated measurements of the temperatures, pressures, and flow rates during pressurant inflow and liquid outflow.
- (2) Measurement of internal tank vapor/liquid temperatures and pressure at least at the beginning and end of the ramp, hold, and expulsion phases of the transfer processes.

Controlled pressurization and expulsion tests will be performed as part of operational liquid transfers from the supply tank(s) to a receiver tank. Tests will start from a specified initial fill level for the individual tests. For all tests, the initial pressure level in the supply tank should be at a specified value, e.g., 1 atm. Procedures during a sequence consisting of a ramp, hold, and expulsion are performed as outlined below:

Ramp.—Initial quiescent tank conditions are recorded. Pressurant is then introduced into the supply tank through the pressurant diffuser until the pressure reaches the desired transfer pressure. Pressurant flow is monitored and actively controlled so that the specified pressure rise rate is maintained.

Hold.—Conditions in the tank are recorded. A short period (on the order of 1 min) is provided to allow tank conditions to stabilize before proceeding with liquid expulsion. Tank pressure should be monitored and maintained constant (by additional pressurant inflow if necessary) during this period.

Expulsion.—Tank conditions are recorded. Liquid outflow is controlled at the desired rate. Tank pressure is maintained at the set point during outflow. Outflow continues until the supply tank is empty as indicated by the liquid/vapor indicators in the outflow line. Alternately, a partial expulsion could be performed that is terminated after a given amount of liquid outflow has been monitored by the flow meter. Once the outflow is complete, the pressurant flow is discontinued and final tank conditions are recorded.

At the conclusion of each test, the supply tank is allowed to vent down to nominal pressure. The tank is refilled and conditioned for the start of the following experiment.

Test Matrix

A suggested sequence of pressurized expulsion tests is listed in Table III. It has been assumed that the tests are conducted with a single supply tank. Each expulsion is preceded by a ramp from a fixed starting pressure and by a brief hold period to stabilize temperatures and pressure prior to expulsion. The starting conditions should be the same for

The tests include the use of autogenous and non-condensable pressurants. Two different acceleration levels (low- and micro-g) are tested to cover settled and unsettled liquid configurations, and the relative influences of surface tension and gravitational forces. Liquid flowrate variation (high/low) will provide data for fast and slow expulsions which will have differing degrees of energy and mass transport between the pressurant and tank fluid. Tank pressure is known to have a strong influence on pressurization and expulsion in 1-g and hence should be varied in low-g tests. The low and high initial fill level conditions allow testing with a partially- and fully-wetted tank wall.

TABLE III.—TEST MATRIX
[Identical matrix for noncondensable pressurant.]

Pressurant	Bond number	Pressurant temperature	Liquid flowrate	Expulsion pressure	Initial fill level
Autogenous	>1	High	Low	Low Low High High Low	High Low High Low High
			↓ High		
			↓	Low High High Low Low	Low High Low High Low
		↓ Low	↓ Low		
			↓	High High Low Low High	High Low High Low High
			↓ High		
			↓	High Low How High High	Low High Low High Low
	↓ <1	↓ High	↓ Low		
			↓	Low Low High High Low	High High High Low High
			↓ High		
			↓	Low High High Low Low	Low High Low High Low
		↓ Low	↓ Low		
			↓	Low High High Low Low	Low High Low High Low
			↓ High		
			↓	High High	High Low

TABLE IV.—ABBREVIATED TEST MATRIX

Pressurant	Bond number	Pressurant temperature	Liquid flowrate	Expulsion pressure	Initial fill level
Autogenous	>1	High	Low	Low	High
↓	>1	High	High	High	Low
↓	<1	Low	Low	Low	Low
↓	<1		High	High	High
Noncondensable	>1		Low	High	High
↓	>1	↓	High	Low	Low
↓	<1	High	Low	High	Low
↓	<1	High	High	Low	High

Data Analysis

- (1) The volume of liquid displaced.
- (2) Heat transfer to the liquid.
- (3) Heat transfer to the tank wall and internal hardware.
- (4) The amount of mass condensed or evaporated.

Data will be analyzed by performing mass and energy balances on the ullage volume from an initial time t_1 to a final time t_2 as follows:

Mass Balance.—A mass balance on the ullage volume gives:

$$m_{u,2} = m_{u,1} + m_{p,1-2} \pm m_{x,1-2} \quad (5)$$

The mass of the pressurant added, $m_{p,1-2}$, is determined by integration of the pressurant flow meter data. The internal tank volume is divided into volume segments corresponding to the axial and radial temperature sensor locations. The initial and final ullage mass, $m_{u,1}$ and $m_{u,2}$, will be obtained by summing the products of density (as a function of temperature and pressure) and volume for each of the volume segments. The interfacial mass transfer term, $m_{x,1-2}$, is then calculated from equation 1.

Energy Balance.—An energy balance of the entire tank and its contents (tank wall, ullage gas, and liquid), assuming that kinetic and potential energy terms are small and that no external work is performed on the system, takes the form:

$$\Delta U = m_p h_p - m_l h_l + Q \quad (6)$$

where ΔU is the total change in system energy (tank wall + gas + liquid), $m_p h_p$ is the energy added by the pressurant gas, $m_l h_l$ is the energy leaving through the liquid outflow, and Q is the energy input from the external environment. The change in system energy can also be determined from the temperature and pressure data for each of the tank volume segments together with the history of the tank wall temperatures. The gas input and liquid output energies will be evaluated from the gas and liquid flow meter data together with their respective temperature and pressure histories.

These mass and energy terms will be used to evaluate the pressurization and expulsion process and to develop and validate analytical models.

Conclusions

Requirements have been presented for an experiment designed to obtain data for low-g pressurization and expulsion of a cryogenic supply tank. The requirements are of a generic nature and applicable to common cryogenic fluids and condensible or noncondensable pressurants. The experiment may be conducted on either the Space Shuttle or a free-flying test platform. The discussion has covered background information, the thermophysical process, preliminary analytical modeling, and experimental requirements. Key parameters, measurements, hardware

requirements, procedures, a test matrix, and data analysis have been specified.

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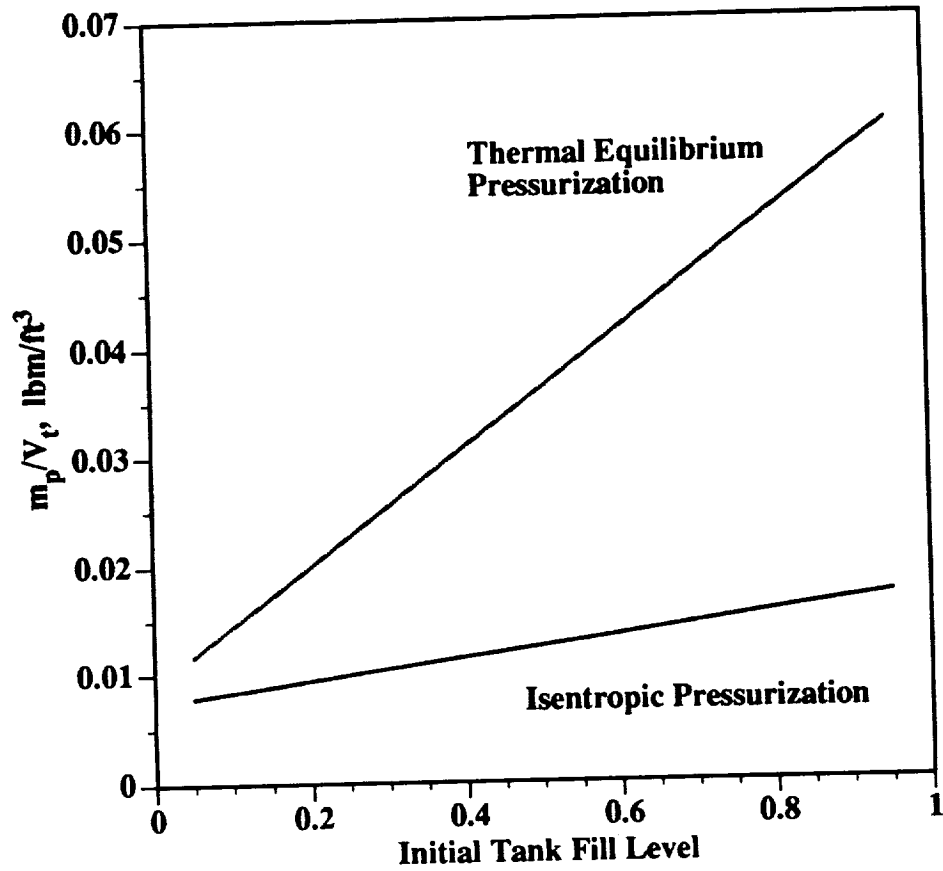


Figure 1 - Comparison of Isentropic and Thermal Equilibrium Models. (predictions are for para-H₂, pressurized from 15 to 40 psia using gaseous H₂ at 100 psia, 520 °R.)



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